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STRUCTURAL ASSESSMENT OF THE MODIFIED TURBINE BLADE ROOT DESIGN

Report No. 90-74-K

B. Teper
Engineer
Applied Mechanics Section
Mechanical Research Department

ABSTRACT

Analyses of the root of a L-1 stage turbine blade from the Nanticoke Thermal Generating station have continued for the past six years. Several blade modifications have been considered. The most recent modification involves a new root and steeple geometry, proposed by the original equipment manufacturer. Results of analyses of the new root geometry are discussed in this report. The new root geometry would require remachining of the L-1 stage discs and full sets of new blades. Finite element analysis showed that the local stress concentrations would be much lower than obtained for the original geometry. Stresses dropped to 50% of the highest stress obtained in the root and to 66% in the disc when compared with the original design (as calculated in the three-dimensional analysis). The new root is structurally advantageous. However, implementation of the design may be expensive and should be balanced against the improved reliability over the anticipated remaining station life.

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EXECUTIVE SUMMARY

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B. Teper
Applied Mechanics Section
Mechanical Research Department

Since the failure of a penultimate stage blade on a Nanticoke 500 MW turbine, a number of finite element stress analyses of the blade and disc have been carried out. The analyses determined if the blade root geometry could be improved to increase blade life by reducing stresses due to centrifugal force. The latest modification of the root geometry is the most promissing improvement considered. In the proposed blade, platform thickness has more than doubled from the original design. The fillet radius below the platform, above the top serration increases from 0.76 mm to 2.18 mm. The slopes of the surfaces in contact between root and disc serrations have been increased from 20° to 42.5° further improving the stress distribution.

Three cases were considered in the 3-D finite element analyses of the new root: full length root and disc without locking groove (only applicable for new rotors), disc with locking groove, and disc with locking groove and blade cut at the base of the locking groove.

Results of the analyses of the new root geometry show much lower stresses than those calculated for the original design. The highest local stress calculated in the three-dimensional analysis in the root dropped from 536 MPa to 263 MPa. The largest stresses in the disc dropped from 294 MPa to 187 MPa. The highest stress in the original root occurred below the trailing edge of the vane near the acute corner, where cracks were found to initiate. In the new design, the highest stress is in the mid-length of the root. This is more advantageous.

Two dimensional analysis of the highest stressed section (from the 3-D analysis) shows that the peak stress above the top serration dropped from 648 MPa (for the 0.76 mm radii) to 467 MPa.

In the redesigned blade/disc arrangement, the locking groove in the disc would remain after remachining. However, it should be cut open at the top. The new root geometry with full length blade is recommended for the station if the improved reliability over the extended station life supports such a high cost modification.

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To Mr. H.J. Kirwin
Manager, Nanticoke
Thermal Generating Station

STRUCTURAL ASSESSMENT OF THE MODIFIED TURBINE BLADE ROOT DESIGN

1.0 INTRODUCTION

Following the failure of an L-1 stage turbine blade in 1983, finite element analysis was carried out to calculate stresses in the existing turbine blade roots. The analysis was extended to include several modifications which could be implemented using existing disc steeples and new blades. The analyzed modifications included:

- removing the locking groove from blade and root
- increasing platform thickness from 6.35 mm to 9.5, 12.7 or 25.4 mm
- increasing radii inside serrations to 1.27 mm (0.050 inch)
- introducing a full length blade without locking groove
- introducing 6.35 mm radii on acute external corners (for shot-peening).

The finite element analyses of all these alternatives showed that the blade will see high local stresses in the root area ranging from 465 to 750 MPa (see Table I). Local stresses in the disc were significantly lower than in the blade root but still high at 282 to 370 MPa. Results of these analyses were described in references /1 and 2/. The modifications produced only small improvements or, in some cases, led to higher stresses.

Efforts to optimize the design of the blade's root and the disc's steeple continue. One such attempt was the new design of the root geometry proposed recently by NEI Parsons and shown in Figure 1. Results of the finite element analysis of this design are presented in this report.

2.0 NEW ROOT GEOMETRY

The new root geometry (shown in Figure 1) can be formed by modifying existing discs. Figure 2 shows the additional material that needs to be removed to form the new root geometry. The new disc geometry would have a smaller outside diameter. The serrations would have a more advantageous angle of contact. The number of serrations remains the same. The blade platform thickness would increase to 13.64 mm to retain the same vane length and steam path geometry.

The region above the locking groove on the back of the disc would be reduced to a set of thin (2 mm) overhanging plates when the disc diameter is reduced. Such thin plates would not contribute to the disc's strength and it could break off or provide a pocket for collecting debris. They should be removed flush with the back of the locking groove.

3.0 FINITE ELEMENT MODEL

The finite element analysis was intended to provide a mechanism for comparing stresses between the proposed and the original root layouts (see Table I). The method used for modeling the blade-disc arrangement used in reference /1/ was retained here:

- The model had approximately the same number of elements and nodes as the previous models
- Disc was included in the model in the same way as in the analyses discussed in reference /1/
- Boundary conditions used in reference /1/ were also used here
- Loading was applied as a centrifugal force in the blade, used in all previous analyses
- Load was transferred from the disc to the blade's root through serration surfaces that were in contact
- Relative motion between the root and disc serrations in contact was not allowed.

Three cases were considered in the analyses. The first model had no locking groove in either disc or blade (see Figure 3). This model was similar to the model described in reference /1/. In the second case, a locking groove was included in the disc only and the blade had a full length root (see Figure 4). In the last model, the blade was cut back so that it did not extend into the locking groove area of the disc (see Figure 5).

The model was created and the results of analyses were processed using PATRAN software. The ABAQUS program was used for the finite element analysis.

4.0 RESULTS OF ANALYSES

4.1 Initial Analysis

Stresses were calculated in the blade and the disc of the model in Figure 3. The general stress distribution changed slightly but the magnitude of stresses dropped significantly. The largest calculated local stress in the root is 265 MPa (see Figure 6) or 49% of stress calculated for the original design. The highest stress in the root is at its mid-length below the vane (see Figure 6a) rather than near the root corners, as was the case before. The largest local stress in the disc is 187 MPa (see Figure 7), or 66% of the calculated stresses in the original design. The highest calculated stress in the disc is still at the lowest serration, but the loading is more uniformly distributed through all serrations, reducing the concentration of stresses in any one area (see Figure 7). Stresses in the center of steeples and blade roots have increased, reducing stresses near surfaces, where cracks have been found in running turbines.

A more detailed two dimensional model through a section of the root was created and is shown in Figure 8. Constant strain four-noded elements were used in generating the model. An analysis was carried out for the area where the highest stress occurred to determine the effect of stress concentrations inside serrations and to compare them with the results from similar analysis in reference /2/. Deformations calculated in the three-dimensional analysis were used as the input load here. The stress distribution in the model is shown in Figure 9. The largest calculated stress of 467 MPa was inside the 2.21 mm radii below the platform. It was similar to the stress calculated in the 2-D analysis for the same location and 1.91 mm radii of the old root design (see reference /2/). The largest contact stress between root and disc occurred in the top serration of the root. At 240 MPa, it is much lower for the new design (see Table II).

4.2 Locking Groove Analysis

A finite element model containing a simplified locking groove is shown in Figure 4. The locking groove is open at the top, as discussed in 2.0 above. The full length blade protrudes through the locking groove creating pockets in the back of the disc. These may have to be closed.

The stress distribution in the model with locking groove in the disc is nearly unchanged from the initial case (see Figures 10 and 11). In Table III, a comparison is made between stresses in various locations above the top serrations for all considered geometries. Introduction of the locking groove in the disc changes stresses in the top serration by less than 11%. The area of highest stress is not affected. Results obtained in the analyses of the original blade design also showed only small changes in stress levels (see Table III and reference /2/).

Stresses in the disc changed slightly. Figure 11b shows a relatively high stress of 165 MPa in the corner of the top serration inside the locking groove.

4.3 Short Blade

If the blade is cut short at the back of the locking groove (see Figure 5), stress distribution in the root changes significantly (see Figure 12). The highest stress of 328 MPa (56% above case 4.2) occurred in the acute corner of the trailing edge. Stresses in the middle of blade length and at the leading edge are nearly the same as in the case with the locking groove (see Table III). Stresses in the disc (containing locking groove) are also nearly unchanged.

5.0 SLIDING BETWEEN SERRATIONS

In the above analyses we assumed that sliding between serrations of the disc and the root would not occur. The models had rigid connections between the two components along surfaces which transmit loads. This assumption is equivalent to the case with very high friction.

The finite element model in Figure 8 was modified to allow for sliding between serrations. The originally imposed deformations of the top of the platform were used in the analyses. Friction coefficients ranged between 0 and 75%. An additional pressure between sliding surfaces was imposed to simulate the interference fit frequently created during assembly. The total compressive force ranged from 0 to 500 kN. Results of the analyses are shown in Figure 13.

If friction is not present, the largest sliding obtained is 0.0314 mm, or 42% of the deformation at the top of the platform. At 0% friction, Von Mises stress is the lowest and reaches about 82% of the stress for the case without sliding. As the friction coefficient increases to 75%, von Mises stress is equal to the stress from the analyses without sliding. Deformation caused by sliding drops to 20% of the platform deformation. If additional pressure is applied between sliding serrations, sliding drops to 8% of the input platform deformation. If the friction coefficient increased above 75% or the total compressive force between contacting serrations increased above 500 kN, no sliding would occur. This case (no sliding) was considered in all past analyses.

The scope of the analyses was limited. Friction coefficients above 75% or compressive force above those shown in Figure 13 caused an unacceptably high numerical error and erroneous results.

6.0 CONCLUSIONS

The new root design offers a significantly improved stress distribution in the root and the disc of a L-1 stage turbine blade. The new turbine blade root configuration should be implemented if the improved blade reliability warrants the expense for the extended life of the generating station.

Sliding was not included in majority of the analyses. High friction coefficient and high forces between serrations imposed during assembly allow for only negligible sliding. Analyses without sliding is a good approximation of the actual case. The highest stresses were obtained for the case where sliding was not present making the analyses conservative.

7.0 FUTURE ACTIVITIES

The above analysis had many simplifying assumptions. We feel that simpler, two-dimensional analyses should continue to assess the effect of some of those assumptions by answering the following questions:

- How do serration tolerances affect stress distribution in the two designs of the root geometry?
- Is the new design sensitive to the size of radii inside serrations?
- Would further geometry optimization be beneficial?

8.0 ACKNOWLEDGMENTS

Dr. T.P. Byrne provided technical review of the project and introduced many ideas contained in the report. Direction of the project together with many valuable comments on the scope of analysis and its direction were provided by Mr. C.T. Moore and Mr. A.C. Davidson. Funding for the project was provided by the Nanticoke TGS. The author acknowledges and thanks them for their valuable contributions.

Reviewed by:

J.D. Tulk
Unit Head-Special Projects & Computing
Applied Mechanics Section

Submitted by:

B. Teper
Engineer
Applied Mechanics Section

Reviewed by:

J.A. Chadha
Section Head
Applied Mechanics Section
Mechanical Research Department

Approved by:

G.J. Clarke
Manager
Mechanical Research Department

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1. M.F. Ishac, T.B. Byrne, *"Nanticoke TGS - Turbine/Disc Investigation, 3-D Finite Element Analysis"*, Ontario Hydro Research Division Report No. 84-101-K, dated August 24, 1987.

2. B. Teper, *"Recommendation for a Modified Design of LP5 Turbine Blade for the Nanticoke TGS"*, Ontario Hydro Research Division Report No. 88-333-K, dated April 20, 1989.

TABLES AND FIGURES

TABLE I

COMPARISON OF STRESSES FROM MODIFICATIONS TO THE 3-D MODEL

No	Model Description		Largest Stress (MPa)		Change from Ref (%)		Comments
	Field of Investigation	Description	Root	Disc	Root	Disc	
1	From Ref. /2/ From Ref. /1/	Reference Design	536	282	100	100	
2		Model before Locking Groove	507	294	95	104	
3	Cutting off Locking Groove	In Root	750	294	140	104	2,4
4		In Disc & Root	694	354	129	125	2,3,4
5	Varying Platform Thickness (Using Ref Design)	9.5 mm Platform	488	284	91	101	1
6		12.7 mm Platform	468	301	87	107	
7		25.4 mm Platform	465	299	87	106	1
8	Full Length Root	Disc with Locking Groove	515	284	96	101	
9		9.5 mm Platform	479	301	89	107	1
10	6.3 mm Radii For Shot-peening	Radius in Root and Disc	582	356	109	126	2,3,4
11		9.5 mm Platform	575	370	107	131	2,3,4
12		Radius in Root Only	578	305	108	108	2,3,4
13		Model without Locking Groove	568	322	106	114	2,3,4
14	New Root Geometry	Locking Groove in Disc Full Blade	265	187	49	66	1
15		Locking Groove in Disc Short Blade	263	187	48	66	1
16			328	186	61	66	1

Comments

1. Beneficial Reduction of High Stresses
2. Disadvantage: Significant Increase in Stresses lin the Root
3. Disadvantage: Significant Increase in Stresses in the Disc
4. Disadvantage: Shift of High Stressed Area to the Acute Corner

TABLE II

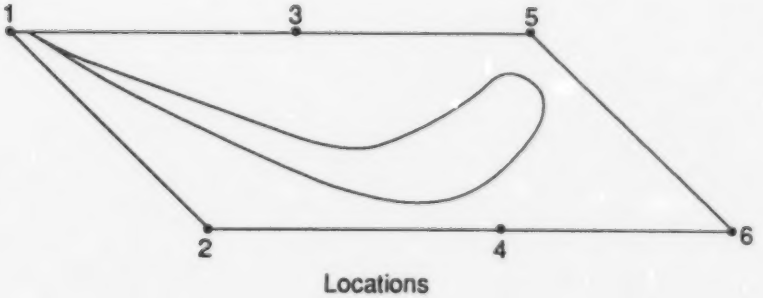
COMPARISON OF STRESSES INSIDE SERRATION RADII

Blade Style	Platform Thickness (mm)	Top Serration Radius		Highest Von Mises Stress (MPa)		
		(inch)	(mm)	Contact	In Radius	In Disc
New	13.64	0.087	2.21	240	467	345
Old	9.5	0.020	0.51	80	805	380
Old	9.5	0.030	0.76	360	648	365
Old	9.5	0.050	1.27	420	569	340
Old	9.5	0.075	1.91	640	505	290

TABLE III

STRESSES IN ROOT ABOVE TOP SERRATION

Model	Locking Groove in Disc	Blade Length	Location of Stress (MPa)					
			1	2	3	4	5	6
New	No	Full	210	53	150	265	240	45
New	Yes	Full	232	45	153	263	240	50
New	Yes	Short	328	78	155	251	240	50
Old	No	Full	507	37	75	380	460	30
Old	Yes	Full	514	50	178	420	455	45
Old	Yes	W/L Groove	535	65	150	390	450	30
Old	Yes	Short	749	30	200	390	460	20



Locations

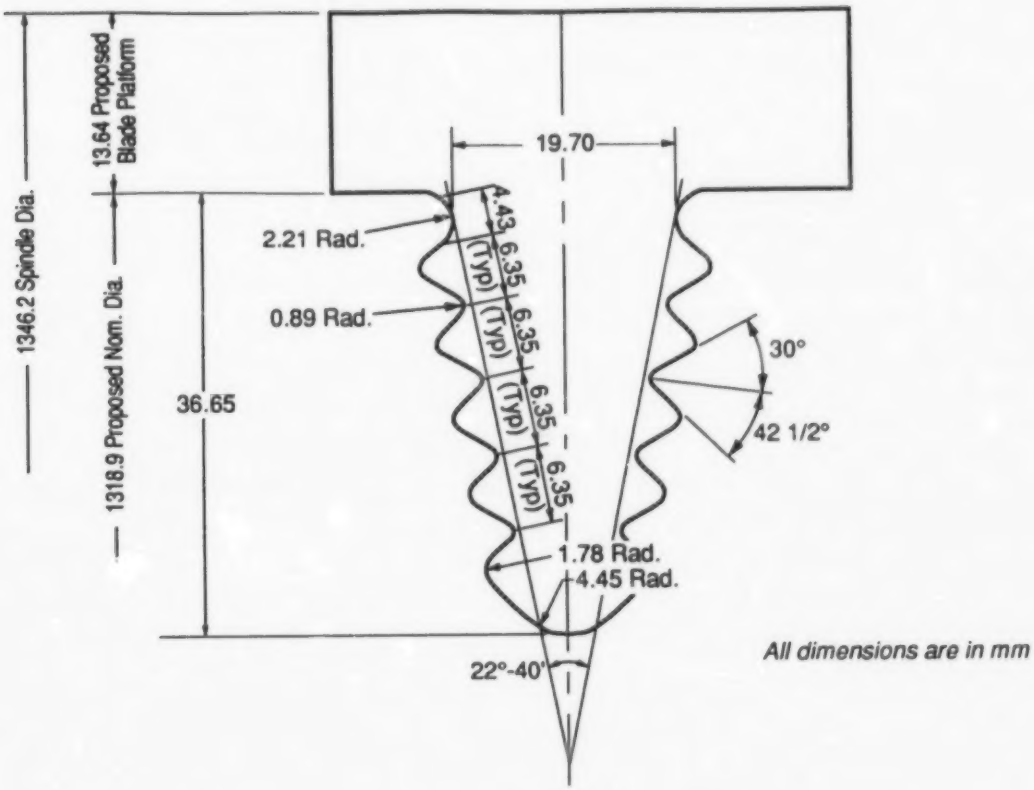


FIGURE 1
NEW ROOT CONFIGURATION

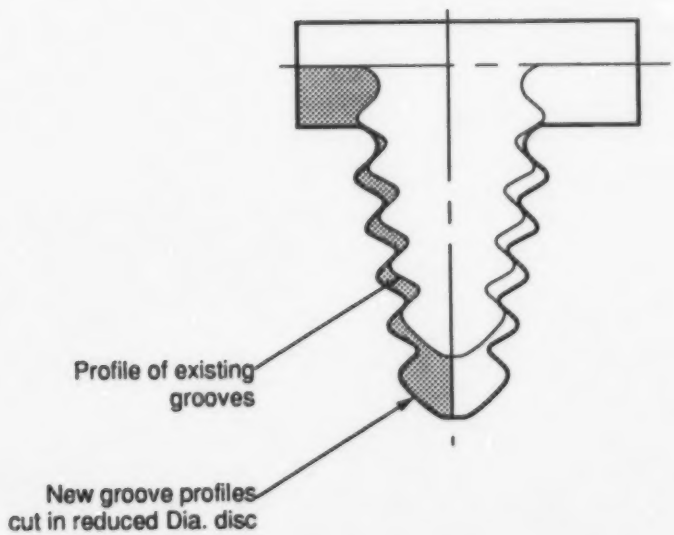


FIGURE 2
DISC MATERIAL TO BE REMOVED FOR THE NEW ROOT GEOMETRY

a) FULL MODEL

b) MODEL OF ROOT AREA

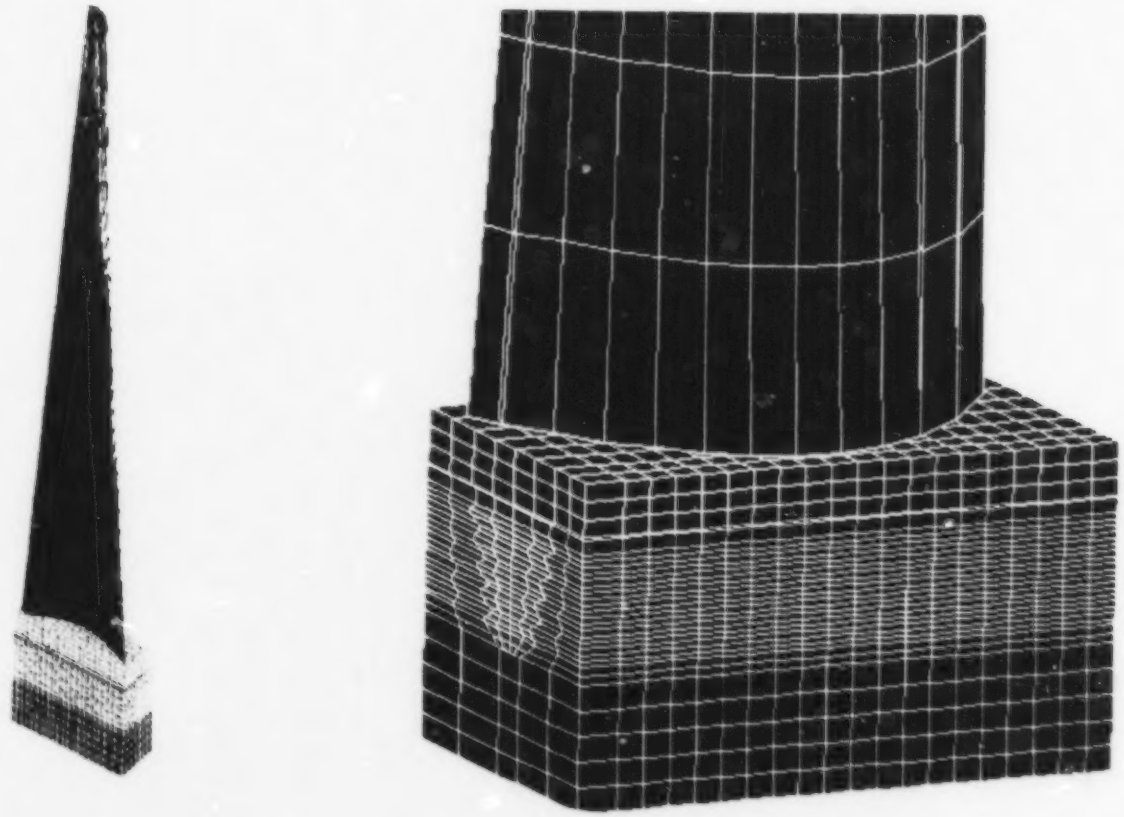


FIGURE 3

FINITE ELEMENT MODEL OF NEW BLADE FOR INITIAL ANALYSIS

FIGURE 4

MODEL OF THE NEW ROOT WITH LOCKING GROOVE IN DISC

FIGURE 5

MODEL WITH LOCKING GROOVE IN DISC AND SHORT BLADE

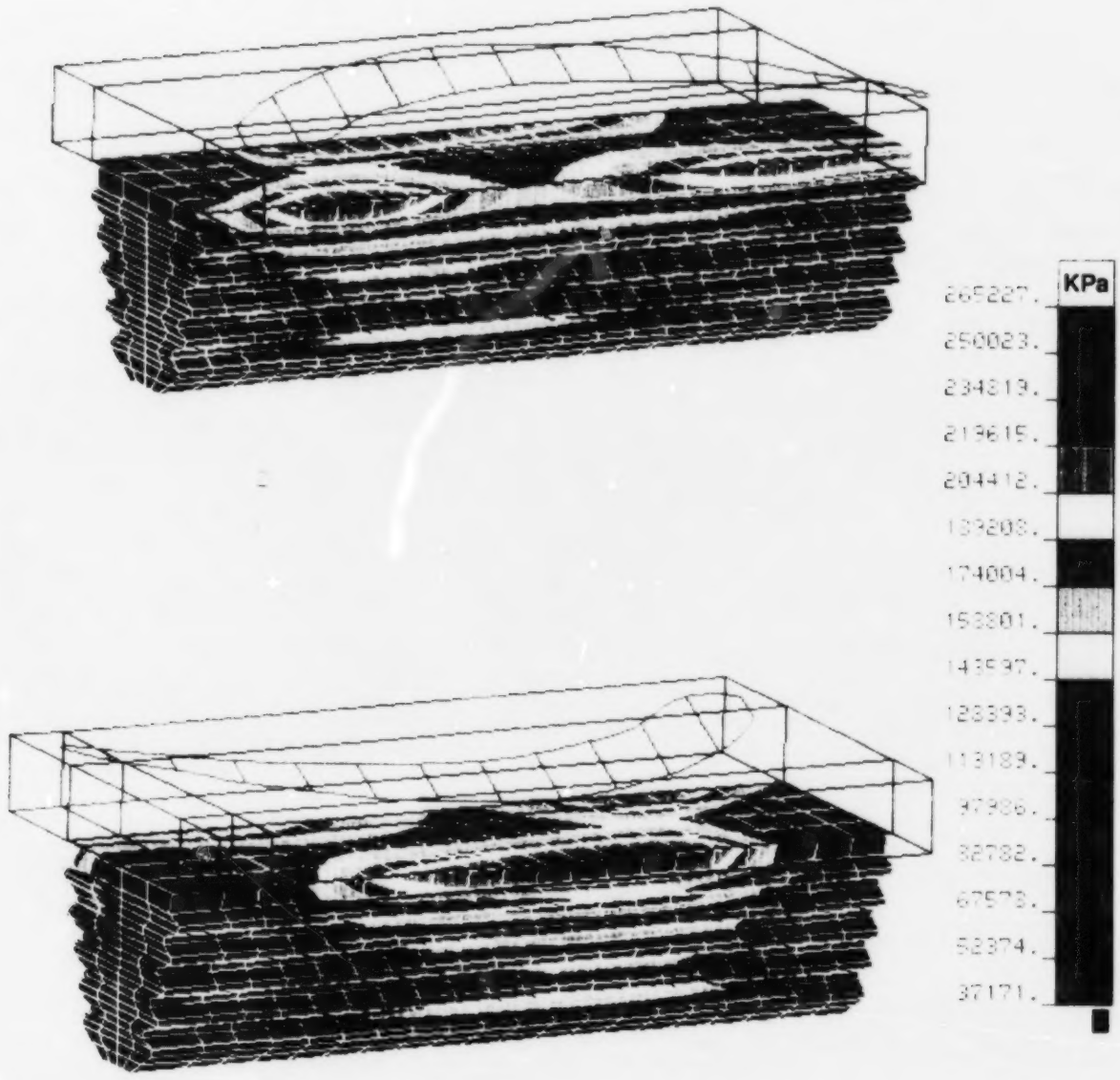
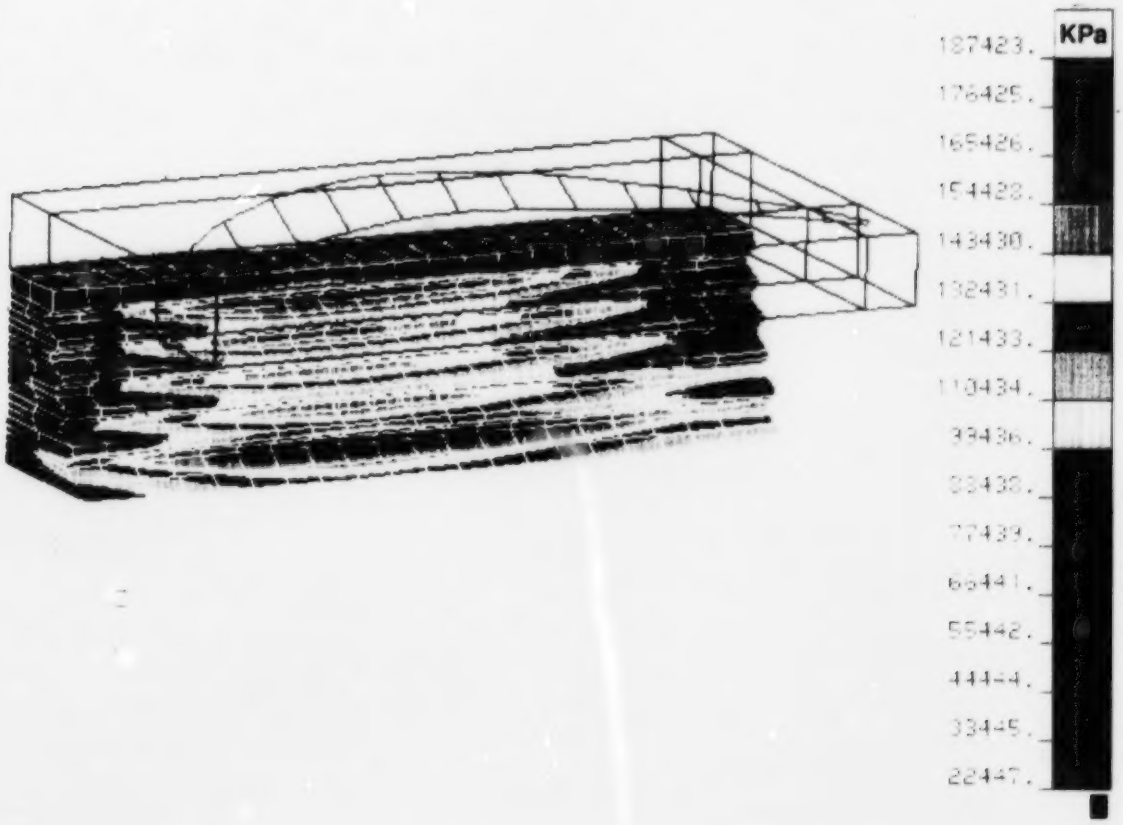


FIGURE 6

STRESS DISTRIBUTION IN THE ROOT OF THE INITIAL MODEL



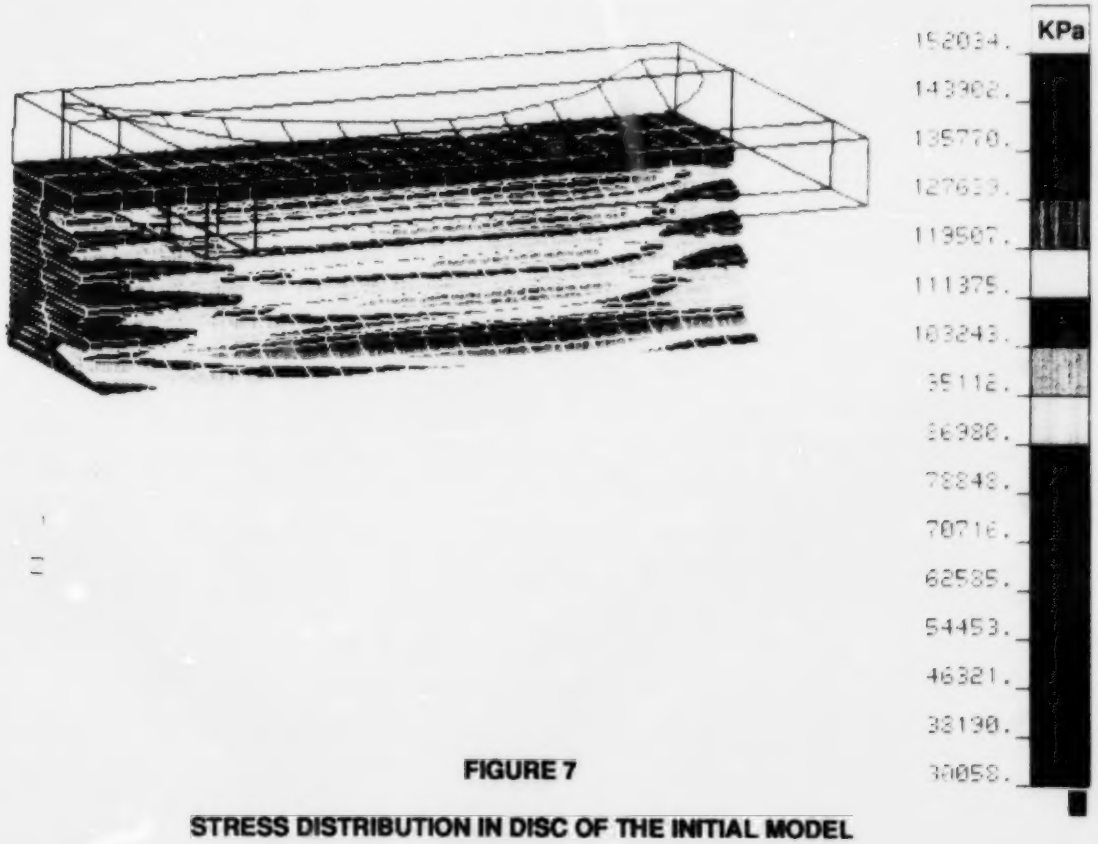


FIGURE 7

STRESS DISTRIBUTION IN DISC OF THE INITIAL MODEL

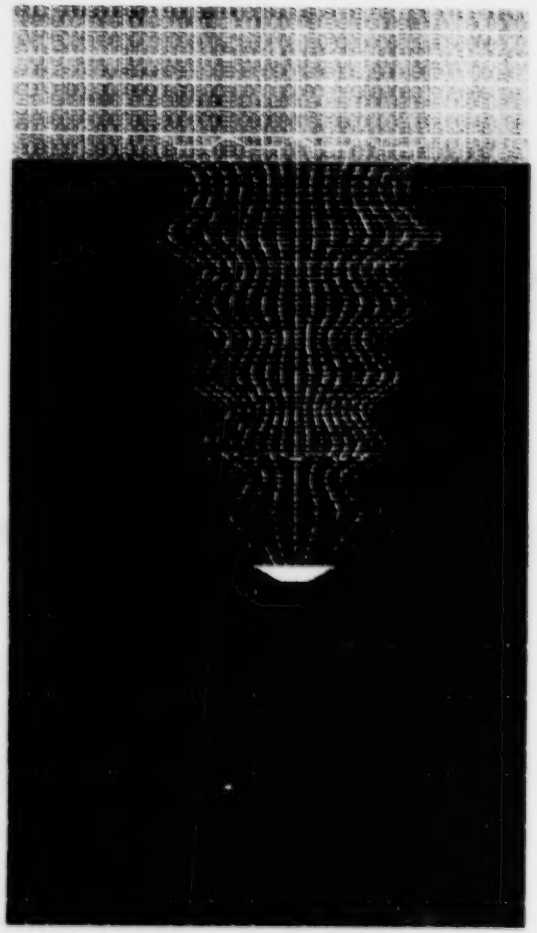


FIGURE 8

TWO-DIMENSIONAL FINITE ELEMENT MODEL

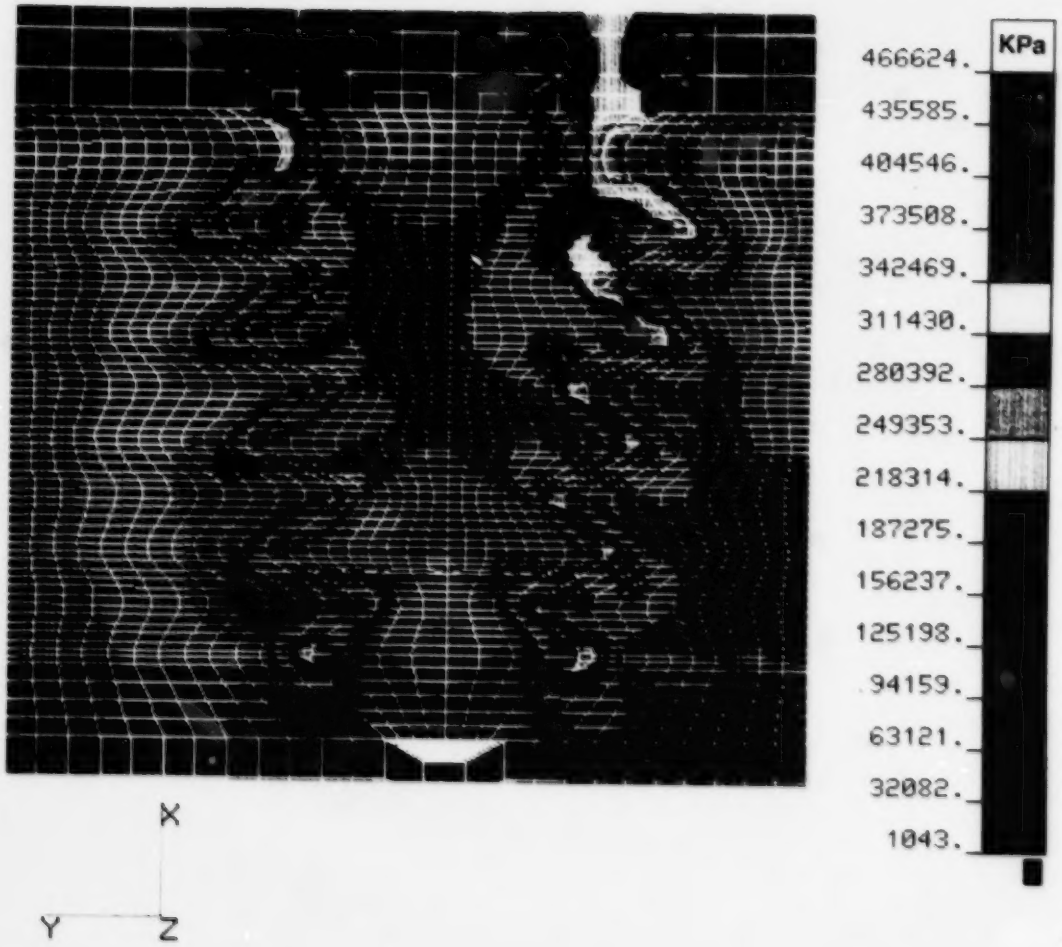


FIGURE 9

STRESS DISTRIBUTION IN THE TWO-DIMENSIONAL MODEL

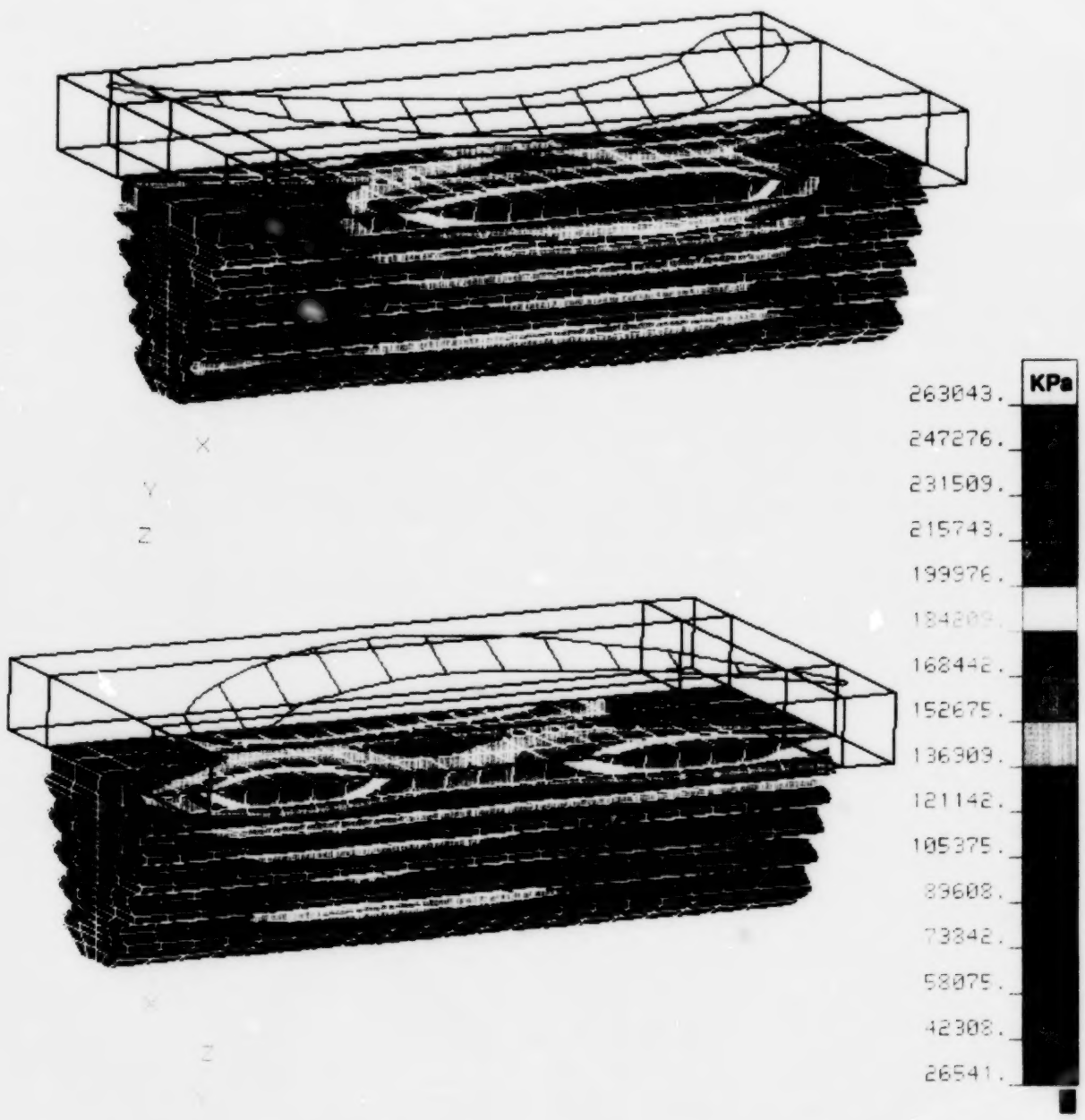


FIGURE 10

STRESSES IN THE ROOT OF THE MODEL WITH LOCKING GROOVE

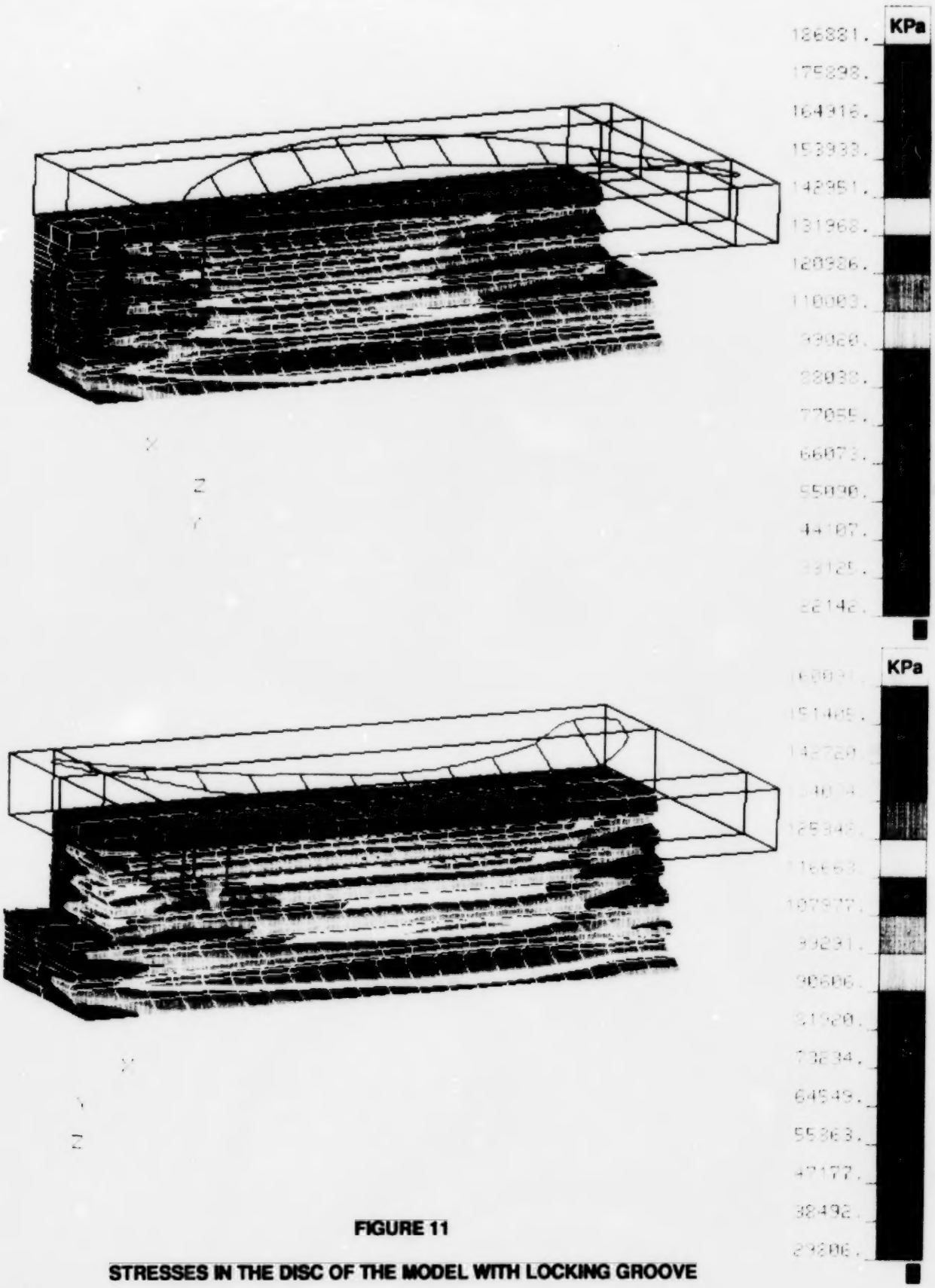


FIGURE 11

STRESSES IN THE DISC OF THE MODEL WITH LOCKING GROOVE

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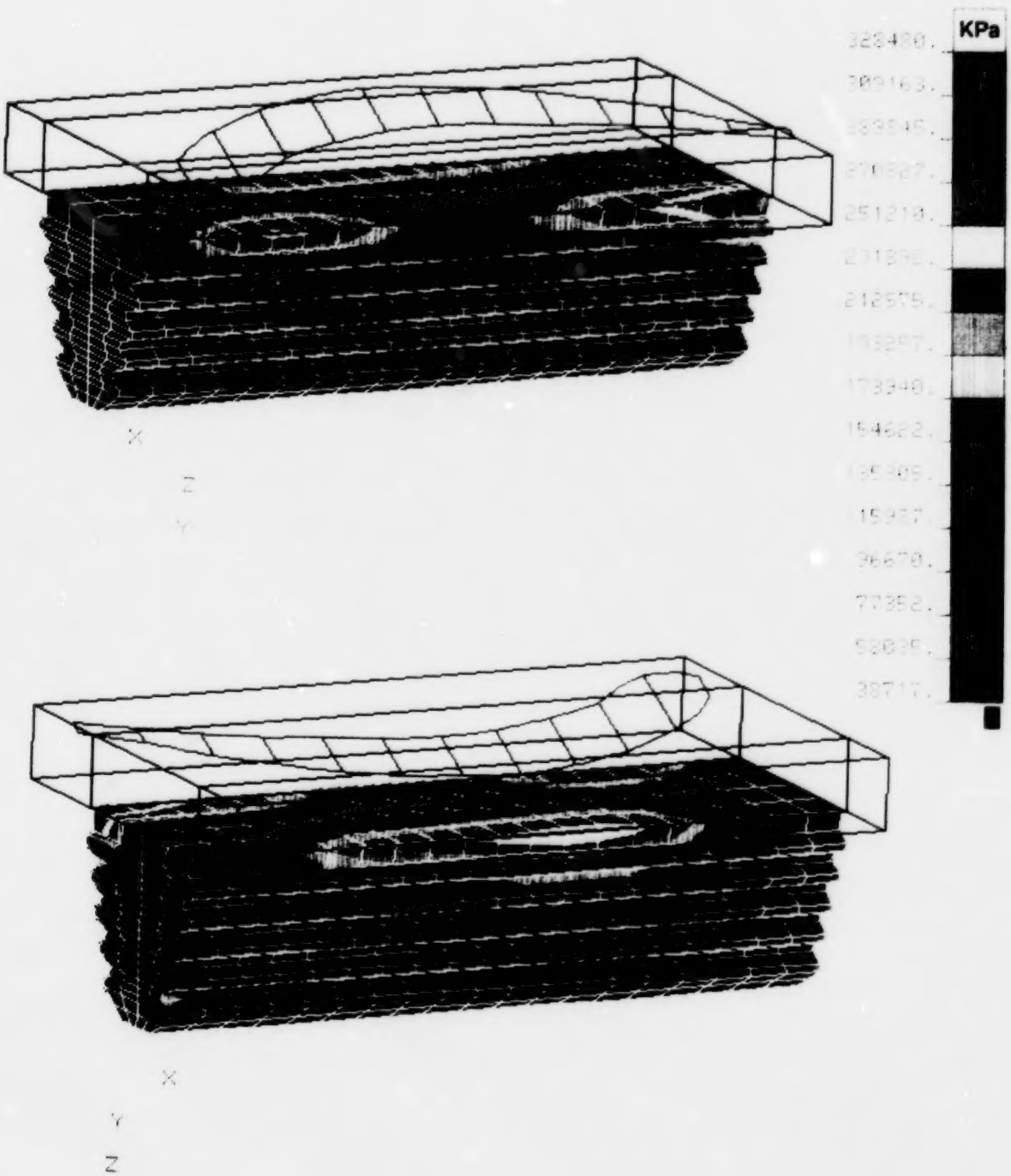

FIGURE 12

STRESSES IN THE ROOT OF THE MODEL WITH SHORT BLADE

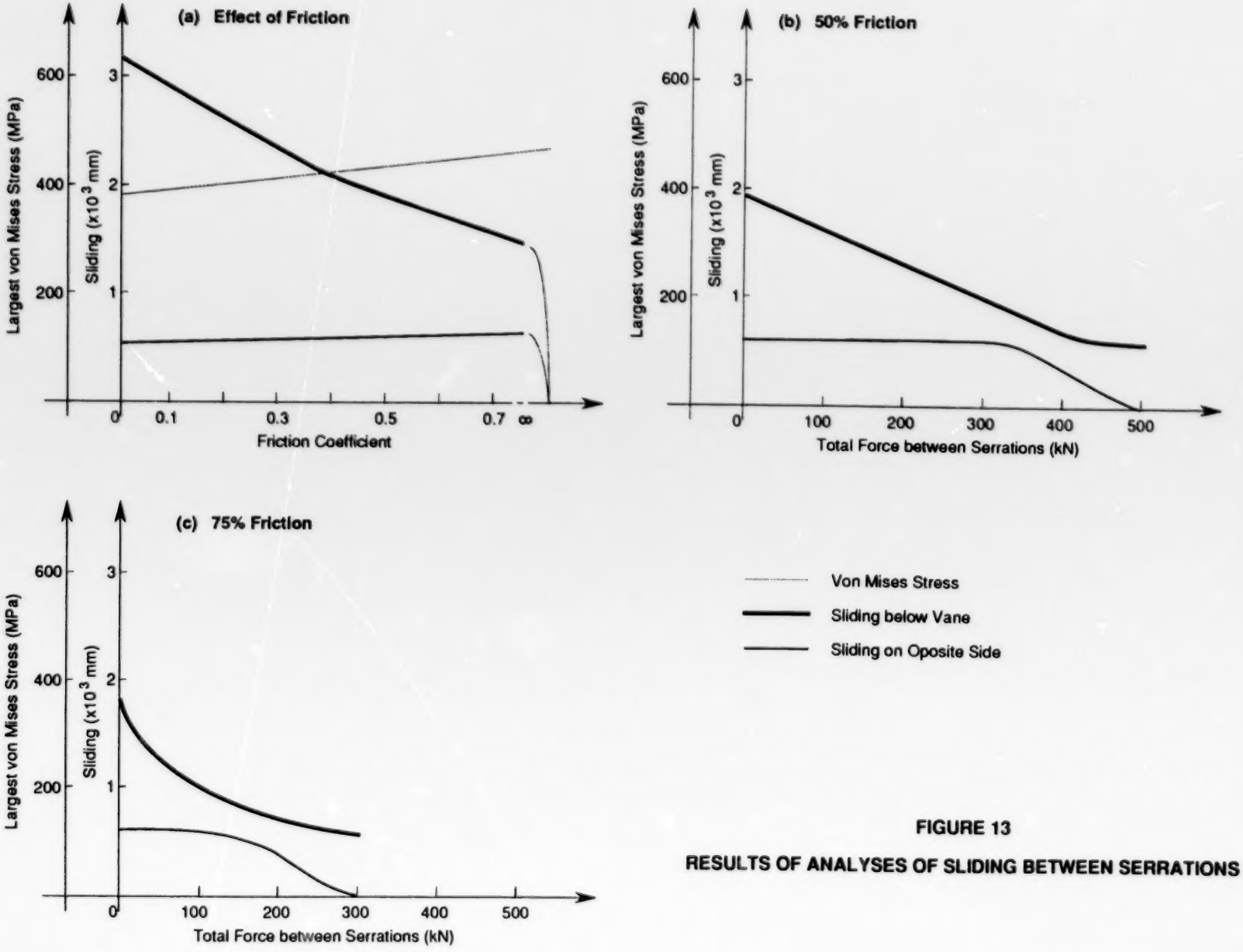

FIGURE 13

RESULTS OF ANALYSES OF SLIDING BETWEEN SERRATIONS